Bridge visual inspections: Experience of local authorities and the case study of the Corso Grosseto viaduct

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ABSTRACT: Visual inspections are traditional method to collect information about bridge condition state. They are performed by qualified inspectors, during the bridge service life, which formulate judgments based on direct observation of the structure. This activity is however influenced by the subjectivity of expert opinions. Moreover, the frequency and the accuracy of bridge inspections may influence future maintenance activities. BRIDGE|50 is a research project aimed at investigating the residual structural performance of a 50-year-old bridge recently dismounted in Italy. The objectives include the validation, both in qualitative and quantitative terms, of national and international bridge inspection procedures through the comparison of the outcomes of visual inspections with the results of experimental tests. The paper describes bridge inspection procedures of local authorities, including Municipality of Turin, Metropolitan City of Turin, and Piedmont Region, and summarizes the visual inspections performed in the BRIDGE|50 research project before the bridge dismounting.

1 INTRODUCTION

Periodic visual inspections represent an easy method to identify the condition state of bridges and viaducts. However, they are conditioned by judgments subjectivity. Guidelines and standard procedures allow to increase the objectivity in the damage evaluation and decide in an optimal way when to inspect a facility (Mori & Ellingwood 1994). Moreover, the integration of visual inspections with monitoring systems may reduce the uncertainties related to the inspector judgements. More in general, bridge inspection procedures may provide condition indicators which allow infrastructure managers to allocate economic resources and prioritize bridge interventions within infrastructure systems (Biondini & Frangopol 2016).

BRIDGE|50 is a research project aimed at investigating the residual structural performance of a 50-year-old bridge recently dismounted in Turin, Italy (Biondini et al. 2020). The objectives of this project include the validation, both in qualitative and quantitative terms, of national and international bridge inspection procedures through the comparison of the outcomes of visual inspections with the results of experimental tests. The paper provides an overview of international methodologies and standards to inspect infrastructure systems, describes bridge inspection procedures of local authorities, including Municipality of Turin, Metropolitan City of Turin, and Piedmont Region, with emphasis on relationship between visual inspections, maintenance programs, and prioritization criteria. Finally, the visual inspections performed in the BRIDGE|50 research project before the bridge dismounting are presented.

2 BRIDGE VISUAL INSPECTION

Visual inspection is the most traditional method to achieve information about the current bridge state. It is performed by qualified inspectors which formulate a judgment about bridge condition on the base of direct observation of the structure. This operation is relatively cheap since it does not involve usually any test or traffic disruption. On the other hand, this kind of activity has some potential limitations related to the subjectivity of expert opinions. The standardization of inspections routines by means of guidelines (Weseman 1995, AASHTO 2013) may reduce the uncertainty associated to the subjective judgment.

Nowadays, the integration of several technologies such as Non-Destructive Tests (NDT), Structural Health Monitoring (SHM) and Unmanned Aerial Vehicles (UAV) into the inspection process may help to identify critical elements and defects that are not visible. However, such technologies are not always available and despite their effectiveness, they cannot totally substitute expert opinions.

Visual inspection results can effectively support the planning of maintenance activities and rehabilitation interventions. Bridge condition indicators allow infrastructure managers and decision-makers to have an overview about the general condition of the bridge stock and represent a basis for allocating resources to bridges within an infrastructural network. Different types of condition indicators have been developed worldwide according to administration needs and aims. Examples can be found in Shepard and Johnson (2001) and Chase et al. (2016).

The Bridge Health Index (BHI) proposed by Shepard and Johnson (2001) assumes that each bridge element has an initial asset value when it is new that will decay to a lower condition state during service life. However, maintenance and rehabilitation interventions can improve the condition of the element as well as its asset value. For the BHI computation, each bridge element is evaluated according to different Condition States (CS). A Weighting Factor WF_i is computed for each condition state CS_i as follows:

$$WF_i = \frac{CS_i - 1}{CS_{i_{max}} - 1} \quad (1)$$

Condition states described in AASHTO (2013) are Good (1), Fair (2), Poor (3), and Severe (4).

Condition information about bridge components are organized as shown in Table 1, with the indication of the Total Element Quantity (TEQ) and the portions Q_i subjected to the considered CS. Failure Cost (FC) can include replacement, administration and user costs and it is generally established by experts. The Total Element Value (TEV) and Current Element Value (CEV) are hence computed for each bridge component j as follows:

$$TEV_j = TEQ_j \cdot FC_j \quad (2)$$

$$CEV_j = \sum_i^4 (Q_i \cdot WF_i) \cdot FC_j \quad (3)$$

The Bridge Health Index BHI for the whole structure is computed as follows:

$$BHI = \frac{\sum_j^n CEV_j}{\sum_j^n TEV_j} \cdot 100 \quad (4)$$

where n is the total number of structural elements.

Chase et al. (2016) proposed a classification of bridge condition indexes, based on the approach used for their quantification:

- *Ratio-Based approach* computes the remaining value of the bridge, making the ratio of the current condition to the condition of the structure when it was new (e.g. BHI).
- *Weighted averaging approach* estimates the condition of the structure by combining condition ratings of all individual bridge elements weighted by their contribution to the structural integrity of the bridge. This approach is typical of systems relying on element-level inspection data.
- *Worst-conditioned component approach* approximates the overall bridge condition indicator to the score of the component in the worst condition. It is common in systems which carry out inspections on key bridge components.
- *Qualitative approach* describes the structure only in linguistic terms such as Poor, Fair or Good, without using numerical scales.

Indicators developed by combining some of the above listed methods have been also proposed in literature.

Table 1: Example of condition and cost information format, adapted from Shepard and Johnson (2001).

Item	Unit	TEQ	CS_1	CS_2	CS_3	CS_4	Cost
j	Length	L	Q_1L	Q_2L	Q_3L	Q_4L	FCj

3 EXPERIENCE IN BRIDGE INSPECTION BY THE MUNICIPALITY OF TURIN

The City of Turin, and in particular its Infrastructure and Mobility Division, manages about 207 road infrastructures divided into river bridges, road and railway bridges and cycle-pedestrian walkways. This infrastructural heritage includes reinforced concrete and steel structures, road systems, retaining devices, subservice networks and other engineering systems (e.g. safety tunnel systems and structural and flood monitoring systems, among others).

A map of the infrastructural system of the city of Turin is illustrated in Figure 1. The management and the maintenance activities of these infrastructures is carried out by qualified technicians, who are responsible of periodic inspections, ordinary and extraordinary maintenance interventions and subsequent supervision of the overall operations.

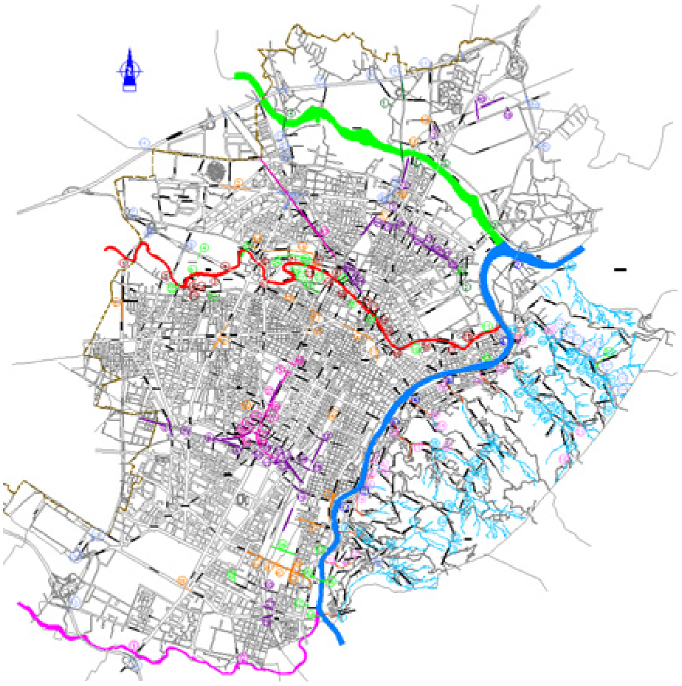


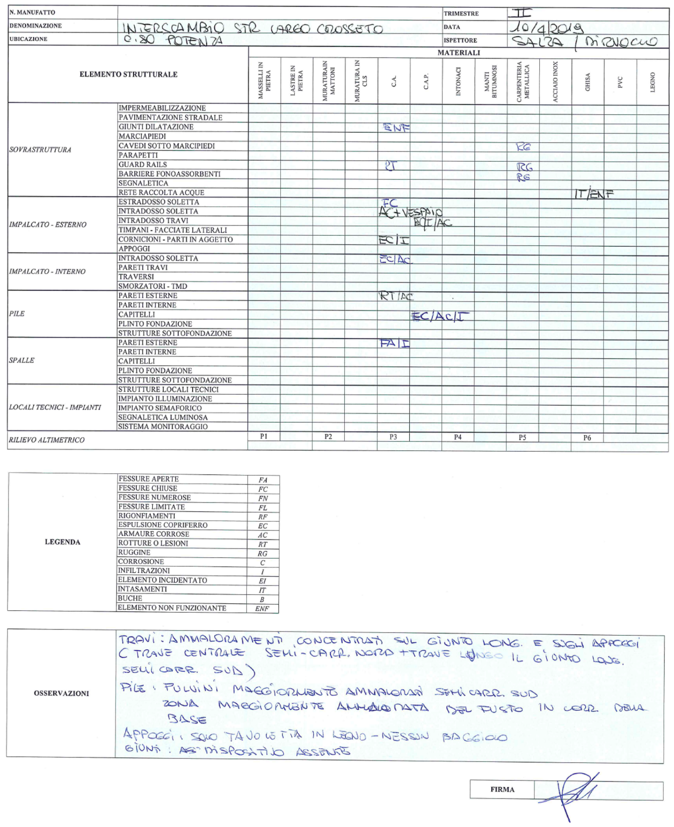
Figure 1. Infrastructural system map of the city of Turin.

3.1 *Inspection criteria*

The inspection of road infrastructures represents the starting point in the management process, and it has a fundamental importance to eventually plan appropriate maintenance and repair interventions. Most of the Italian infrastructural heritage is reaching the end of their service life. In particular, most of reinforced concrete infrastructures have been built between the 60s and 70s and therefore they exhibit more than 50 years of lifetime. In the last years, the city of Turin implemented its own bridge inspection procedure based on three types of activities:

- Activity 1: On-site periodic inspections (every six months), carried out by qualified technicians and bridge inspectors. The aim is the filling out of forms for the identification of the condition state of the structural and non-structural bridge elements. An example of a periodic inspection form is reported in Figure 2.

- Activity 2: Check of the compiled forms by a supervisor engineer, who translates the collected data and judgements into numerical coefficients to be included in a computer database. This dataset includes evaluations, based on a defect index (DI), for the entire managed infrastructural systems. In this way, the infrastructure managers and decision-makers can define a scale of priority intervention, assess the need to carry out further investigations, plan maintenance interventions and find the related financial coverage.



N. MANUFATTO		TRIMESTRE	II
DENOMINAZIONE	INTERSCAMBIO STR LARGO GROSSETO	DATA	10/4/2019
UBICAZIONE	C.SO POTENZA	ISPETTORE	SALZA / DI RUOCCO

ELEMENTO STRUTTURALE		MASSELLI IN PIETRA	LASTRE IN PIETRA	MURATURA IN MATTONI	MURATURA IN CLS	C.A.	C.A.P.	INTONACI	MANTI BITUMNOSI	CARPENTERIA METALLICA	ACCIAIO INOX	GHISA	PVC	LEGNO
SOVRASTRUTTURA	IMPERMEABILIZZAZIONE													
	PAVIMENTAZIONE STRADALE													
	GIUNTI DILATAZIONE					ENF								
	MARCIAPIEDI													
	CAVEDI SOTTO MARCIPIEDI									RG				
	PARAPETTI													
	GUARD RAILS					RT				RG				
	BARRIERE FONOASSORBENTI									RG				
	SEGNALETICA													
	RETE RACCOLTA ACQUE											IT/ENF		
IMPALCATO - ESTERNO	ESTRADOSSO SOLETTA					FC								
	INTRADOSSO SOLETTA					AC+VESPAIO								
	INTRADOSSO TRAVI						EC/I/AC							
	TIMPANI - FACCIATE LATERALI													
	CORNICIONI - PARTI IN AGGETTO					EC/I								
	APPOGGI													
IMPALCATO - INTERNO	INTRADOSSO SOLETTA					EC/AC								
	PARETI TRAVI													
	TRAVERSI													
	SMORZATORI - TMD													
PILE	PARETI ESTERNE					RT/AC								
	PARETI INTERNE													
	CAPITELLI						EC/AC/I							
	PLINTO FONDAZIONE													
	STRUTTURE SOTTOFONDAZIONE													
SPALLE	PARETI ESTERNE					FA/I								
	PARETI INTERNE													
	CAPITELLI													
	PLINTO FONDAZIONE													
	STRUTTURE SOTTOFONDAZIONE													
LOCALI TECNICI - IMPIANTI	STRUTTURE LOCALI TECNICI													
	IMPIANTO ILLUMINAZIONE													
	IMPIANTO SEMAFORICO													
	SEGNALETICA LUMINOSA													
	SISTEMA MONITORAGGIO													
RILIEVO ALTIMETRICO		P1		P2		P3		P4		P5		P6		

LEGENDA		
	FESSURE APERTE	FA
	FESSURE CHIUSE	FC
	FESSURE NUMEROSE	FN
	FESSURE LIMITATE	FL
	RIGONFIAMENTI	RF
	ESPULSIONE COPRIFERRO	EC
	ARMAURE CORROSE	AC
	ROTTURE O LESIONI	RT
	RUGGINE	RG
	CORROSIONE	C
	INFILTRAZIONI	I
	ELEMENTO INCIDENTATO	EI
	INTASAMENTI	IT
	BUCHE	B
	ELEMENTO NON FUNZIONANTE	ENF

OSSERVAZIONI

TRAVI: AMMALORAMENTI CONCENTRATI SUL GIUNTO LONG. E SUGLI APPOGGI (TRAVE CENTRALE SEMI-CARR. NORD + TRAVE LUNGO IL GIUNTO LONG. SEMI CARR. SUD)
PILE: PULVINI MAGGIORMENTE AMMALORATI SEMI CARR. SUD
ZONA MAGGIORMENTE AMMALORATA DEL FUSTO IN CORR. DELLA BASE
APPOGGI: SOLO TAVOLETTA IN LEGNO - NESSUN BAGGIOLO
GIUNTI: DISPOSITIVO ASSENTE

FIRMA

Figure 2. Periodic inspection form filled out by the Turin municipality during on-site inspections.

- Activity 3: Execution of on-site destructive and non-destructive tests if the information contained in the inspection forms are not sufficient to identify the actual deterioration state. Structural tests allow to investigate areas and structural elements which may not be easily inspected with a visual examination. They can also quantify mechanical characteristics of bridge materials. The information achieved through experimental tests are then included in the documentation used to plan the repair and maintenance project.

An example of infrastructure databased adopted by the Municipality of Turin is reported in Figure 3.

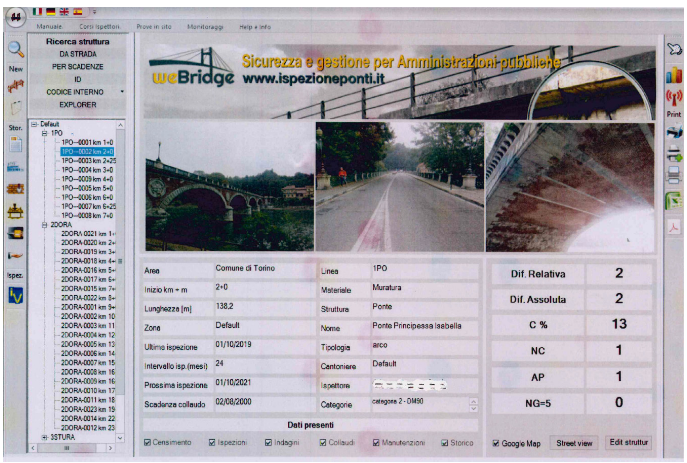


Figure 3. Infrastructural system database, from weBridge software (www.ispezioniponti.it).

The catastrophic events of bridge failures in the last decades, like the partial collapse of Morandi bridge (Italy, 2018) and the progressive collapse of Nanfang'ao Bridge (Taiwan, 2019) raised the attention worldwide on bridge periodic inspection and maintenance. The Italian Ministry of Infrastructure and Transport recently promoted a campaign of extraordinary inspection and verification of about 111 infrastructures, consisting in defining:

- Increases in traffic and live loads with respect to the actions considered during bridge design.
- Defects with respect to seismic actions identified with a simplified structural model.
- Deficiencies related to structural robustness.
- Shortcomings in terms of material durability.

The obtained results (currently still in the final development phase) can be adopted to define a single condition state index to be used for the definition of the intervention priority and consequently to proceed with the planning, design and execution of appropriate maintenance and repair interventions.

4 EXPERIENCE IN BRIDGE INSPECTION BY THE METROPOLITAN CITY OF TURIN

Starting from the early 2000s, the Metropolitan city of Turin, the Politecnico di Torino and the Aster S.r.l. company, promoted a research work with the aim of identifying and creating a simple tool for the management of road bridges and viaducts. To achieve this goal, the maintenance structural program was divided into two phases:

- A first phase in which the basic information of the investigated viaduct are collected. The initial activity consists in determining the actual state of each bridge by acquiring essential information, like geometric, material and loading data, and a photographic documentation of the system which may capture its condition state.

- Based on the information obtained in the preliminary level, in the second phase appropriate interventions are planned. The operations may consist on in-depth inspections, structural destructive or non-destructive tests, and ordinary and extraordinary maintenance interventions. A more detailed structural investigation can be also required if the first phase is unsatisfactory to judge the degradation state of the bridge.

The obtained structural information allow to analytically define the damage state detected on each structural system in order to define a priority intervention scale. Bridge priority rankings can be used to allocate and optimize economic resources. Moreover, they allow to identify critical situations which require immediate intervention or bridges which may require future investigations. Once the condition state of a structural system has been investigated, the in-time updating of the collected information is a fundamental task to plan future interventions. This is carried out through a management database periodically updated and consulted. Moreover, it is fundamental to ensure an adequate periodicity of the inspections based on results of previous inspections. The flowchart of the bridge inspection procedure used by the Metropolitan City of Turin is present in Figure 4.

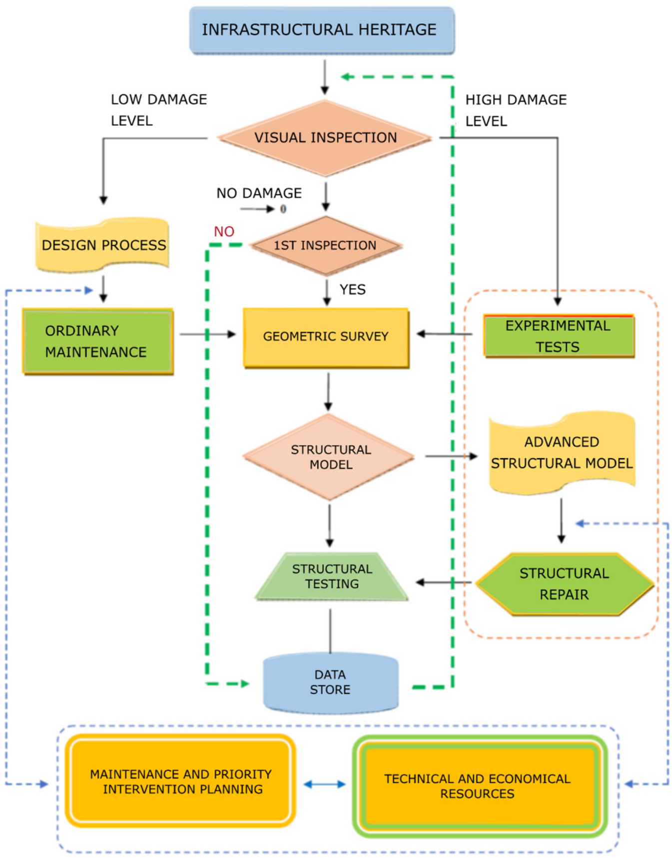


Figure 4. Flowchart of the bridge inspection procedure of the Metropolitan City of Turin.

Besides geometrical and material information of bridges, the damage typology, the damage extent and its time-evolution have to be quantified. Each type of structural and non-structural damage is identified by an alphanumeric code. A letter is given based on damage typology, like structural cracks, steel corrosion or water infiltration, among others. Then, two numerical coefficients are introduced. They are related to:

- Damage severity D_s: a numerical value from 1 to 8 is assigned based on the intensity of the damage. The evaluation is reported in Table 2.
- Damage extension D_e: a value equal to 1 is assigned to extended damages and a value equal to 0.25 is attributed to a localized damage. Regarding structural cracks, the damage extension coefficient is always equal to 1.

Table 2: Severity of structural damage.

Level	Type of damage	D_s
1	Non-structural damage, to be renewed with ordinary maintenance	1
2	Non-structural damage, to be renewed with extraordinary maintenance	2
3	Minimum structural damage	3
4	Advanced structural damage	4
5	High structural damage	5
6	Important structural damage	8

Each type of structural and non-structural damage k is evaluated through a damage index DI_k combining the damage severity and the damage extension coefficient, as follows:

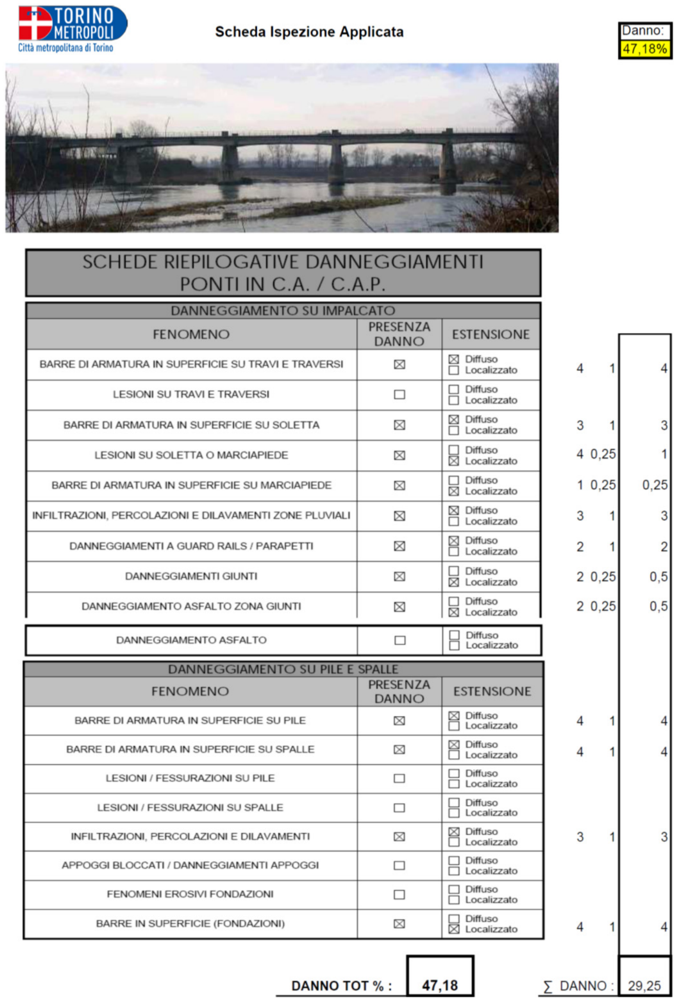
$$DI_k = D_{s_k} \cdot D_{e_k} \tag{5}$$

A bridge damage index BDI is formulated as follows:

$$BDI = \frac{\sum_k^n DI_k}{n \cdot (D_s = 8) \cdot (D_e = 1)} \cdot 100 \tag{6}$$

Where n is the total number of detected damages and the denominator represents the worst bridge damage evaluation. The bridge damage index is reported into a percentage basis to achieve a ranking scale between the entire infrastructural heritage analyzed by the Metropolitan City of Turin. The results represent a useful tool to plan ordinary and extraordinary maintenance activities. They can also be used for additional investigation or urgent repair interventions. An example of bridge damage inspection report of an existing RC bridge, adopted by the Metropolitan City of Turin, is illustrated in Figure 5.

An additional concern of the Metropolitan City of Turin is the assessment of hydraulic vulnerability of existing river bridges to ensure the infrastructural network functionality. The bridge hydraulic vulnerability is a time-dependent property due to the time-evolution of water effects. Defects related to floods and water-induced erosion are generally partially identifiable during visual inspections. It is therefore important to adopt a monitoring system capable of following the evolution of the structure-river interaction and update safety conditions of the bridge.



TORINO METROPOLI
Città metropolitana di Torino
Scheda Ispezione Applicata
Danno: 47,18%

SCHEDE RIEPILOGATIVE DANNEGGIAMENTI PONTI IN C.A. / C.A.P.

DANNEGGIAMENTO SU IMPALCATO					
FENOMENO	PRESENZA DANNO	ESTENSIONE			
BARRE DI ARMATURA IN SUPERFICIE SU TRAVI E TRAVERSI	☒	☒ Diffuso ☐ Localizzato	4	1	4
LESIONI SU TRAVI E TRAVERSI	☐	☐ Diffuso ☐ Localizzato			
BARRE DI ARMATURA IN SUPERFICIE SU SOLETTA	☒	☒ Diffuso ☐ Localizzato	3	1	3
LESIONI SU SOLETTA O MARCIAPIEDE	☒	☐ Diffuso ☒ Localizzato	4	0,25	1
BARRE DI ARMATURA IN SUPERFICIE SU MARCIAPIEDE	☒	☐ Diffuso ☒ Localizzato	1	0,25	0,25
INFILTRAZIONI, PERCOLAZIONI E DILAVAMENTI ZONE PLUVIALI	☒	☒ Diffuso ☐ Localizzato	3	1	3
DANNEGGIAMENTI A GUARD RAILS / PARAPETTI	☒	☒ Diffuso ☐ Localizzato	2	1	2
DANNEGGIAMENTI GIUNTI	☒	☐ Diffuso ☒ Localizzato	2	0,25	0,5
DANNEGGIAMENTO ASFALTO ZONA GIUNTI	☒	☐ Diffuso ☒ Localizzato	2	0,25	0,5
DANNEGGIAMENTO ASFALTO	☐	☐ Diffuso ☐ Localizzato			

DANNEGGIAMENTO SU PILE E SPALLE					
FENOMENO	PRESENZA DANNO	ESTENSIONE			
BARRE DI ARMATURA IN SUPERFICIE SU PILE	☒	☒ Diffuso ☐ Localizzato	4	1	4
BARRE DI ARMATURA IN SUPERFICIE SU SPALLE	☒	☒ Diffuso ☐ Localizzato	4	1	4
LESIONI / FESSURAZIONI SU PILE	☐	☐ Diffuso ☐ Localizzato			
LESIONI / FESSURAZIONI SU SPALLE	☐	☐ Diffuso ☐ Localizzato			
INFILTRAZIONI, PERCOLAZIONI E DILAVAMENTI	☒	☒ Diffuso ☐ Localizzato	3	1	3
APPOGGI BLOCCATI / DANNEGGIAMENTI APPOGGI	☐	☐ Diffuso ☐ Localizzato			
FENOMENI EROSIVI FONDAZIONI	☐	☐ Diffuso ☐ Localizzato			
BARRE IN SUPERFICIE (FONDAZIONI)	☒	☐ Diffuso ☒ Localizzato	4	1	4

DANNO TOT % : 47,18 ∑ DANNO : 29,25

Figure 5. Example of bridge damage inspection report adopted by the Metropolitan City of Turin.

5 EXPERIENCE IN BRIDGE INSPECTION BY THE PIEDMONT REGION

In the historical period which we are nowadays facing, economic resources are limited to plan maintenance interventions to the entire infrastructural heritage. It is a priority for public administrations, as the Piedmont Region, to ensure the use of economic resources according to a reliable process of programming and financing the inspection and repair interventions.

In order to define an accurate and realistic scale of priorities and finalize the available resources, the objective is to adopt a standardized bridge inspection procedure.

Intervention priority criteria are generally based on conditions strictly related to safety of human life, and to reduction of safety margins over time. However, it is essential that the intervention priority scale is based on deficiencies and defects identified in a structure due to external actions and environmental attacks. The bridge inspection procedure of Piedmont region is currently under development. It will be based on a first assessment phase to define bridge priorities and a second phase where in-depth technical and economical evaluation of the planned interventions will be carried out. To define bridge priority interventions some experimental tests will be adopted:

- Extraction of concrete split cores to check carbonation depth and possible steel corrosion effects.
- Measure of relative vertical displacement due to service live loading using a chain of incline-meters arranged on the two sides of the deck.
- Dynamic vibration measurements through an adequate number of triaxial accelerometers located along the bridge deck.

Combining the experimental measures with the judgments from visual inspections a global deficiency index will be defined. It will allow the definition of a priority intervention scale. Moreover, since aging and deterioration are time-dependent processes also the maintenance interventions have to be planned in time. This procedure will allow to define a time-variant priority scale.

6 INSPECTION ACTIVITIES AND MAINTENANCE PLANNING

Bridges are complex structural systems, whose condition states may not be possible to completely observe during the entire service life. For this reason, inspections aimed at determining the condition of the system at a fixed time, play an important role and have to be part of maintenance strategies. Generally, visual inspections may determine only the level of degradation experienced by the structural system. More advanced methodologies, like continuous monitoring systems or protective systems, may determine whether the system is reliable or not with respect to limit conditions. Anyhow, visual inspections return important information to the owner which can be used to schedule future appropriate interventions. However, bridge maintenance costs should also include the inspections costs and all the possible variables which may be connected to them, like the cost of access to the structure, the cost of destructive or non-destructive tests and the cost of structural monitoring, among others. Therefore, the definition of a maintenance strategy is strongly related to the inspection policy. An effective description of the relationship between inspection and maintenance policies is shown in Figure 6 (Sanchez-Silva & Klutke 2016). This scheme allows to underline that strategies used to evaluate the condition state of the system are crucial to an effective maintenance intervention. Sometimes, the maintenance procedure is addressed independently from the inspection policy by the decision-makers.

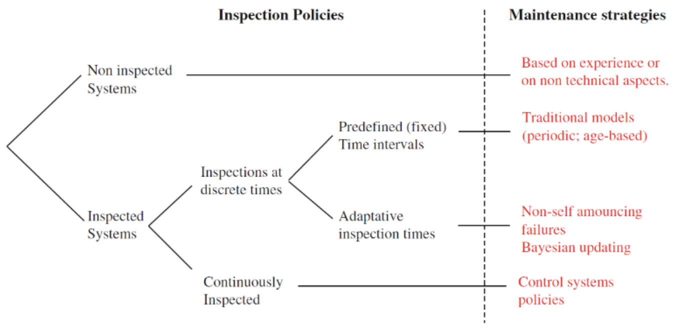


Figure 6. Relationship between inspection and maintenance policies; adapted from Sanchez-Silva and Klutke (2016).

7 VISUAL INSPECTION PROCEDURES OF THE CORSO GROSSETO VIADUCT

Corso Grosseto viaduct is a 80-span 50-year-old concrete bridge recently dismantled in Turin, Italy (Figure 7). The BRIDGE|50 is aimed at investigating the residual structural performance of the viaduct based on an experimental campaign. The project has been framed in the context of the Torino-Ceres railway construction works and it is part of a research agreement involving universities, public authorities, and private companies, including: Politecnico di Milano, Politecnico di Torino, Piedmont Region, City of Turin, Metropolitan City of Turin, Lombardi Engineering, TNE Torino Nuova Economia, ATI Itinera & C.M.B., ATI Despe & Perino Piero, and Quaranta Group.

Figure 7. Corso Grosseto viaduct during dismounting.

A campaign of experimental tests will be performed on a series of deck beams and pier caps dismounted from two adjacent spans and moved in a testing site. The preliminary activities of this project before the bridge dismounting included bridge visual inspections of the two bridge spans of concern.

Visual inspections have been conducted according to national and international standards. The participants have been organized in inspection teams involving several national public authorities and private managing bodies. Each group filled one or more bridge inspection forms according to different standards established in Italy and other countries, including United States and Canada (Figure 8).

Figure 8. Bridge inspection procedures and standard forms.

The diversified amount of data gathered through this activity will be elaborated according to inspection models typically used in practice. Data from visual inspections will be compared with the outcomes of the experimental tests that will be performed on the structural elements investigated. Multiple load tests are planned, including tests of the deck beams under service loadings (elastic behavior), in the post-elastic phase (damaged members), and up to collapse. Different types of bending and shear failures will be also investigated. This will allow to validate, both in qualitative and quantitative terms, the effectiveness, representativeness, and accuracy of existing bridge inspection procedures.

8 CONCLUSIONS

The paper has been devoted to discuss advantages and limitations of bridge visual inspections by providing an overview of international methodologies and standards to inspect infrastructure systems and experience form Italian local authorities involved in the BRIDGE|50 research project. The methods presented are based on different levels of investigation and standards for quantitative evaluation of bridge damages and prioritization intervention criteria. The visual inspection procedures performed within the BRIDGE|50 research project have been also discussed. The objectives of this project include the validation, both in qualitative and quantitative terms, of national and international bridge inspection procedures through the comparison of the outcomes of visual inspections with the results of a campaign of experimental tests on bridge components, including prestressed deck beams and pier caps.

ACKNOWLEDGMENTS

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